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THE EFFECT OF SUPPRESSION DIODES IN FUEL PUMP CIRCUITS

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MRL 91-085 (TR) July, 1991

Canada

92-01189/

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19 pp

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THE EFFECT OF SUPPRESSION DIODES IN FUEL PUMP CIRCUITS

by

E.E. Dainty[1] and G. Lobay[2]

ABSTRACT

This work supplements previous work concerning investigations of the electrical safety aspects of various fuels, in relation to the electrical equipment found in automotive fuel tanks. The previous work assessed such aspects as the relative ignitability by electrical means of various types of methanol mixtures and other fuels through a range of temperatures, in conjunction with the electrical circuits of submersible automotive electric fuel pumps and with fuel level sensing circuits and apparatus.

One aspect which suggested further investigation was the use of suppression diodes to extend the safe operating range of fuel pumps in explosive atmospheres, since the previous work determined that some fuel pump circuits are ignition-capable in the vapour space of a fuel tank under certain conditions. This work determined that the success of the suppression diode method depended on the operating point of the pump, and the type of pump tested. In general, the relatively high current characteristic of fuel pumps makes the use of suppression diodes for enhancing the electrical safety of these circuits a marginal proposition.

KEYWORDS: Fuel tanks, suppression diodes, fuel pumps, intrinsic safety, fuel tank explosions

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L'effet des diodes de suppression installés dans les circuits de pompes à carburant

par
E.E. Dainty[1] et G. Lobay[2]

Résumé

Ce document sert de complément aux travaux antérieurs portant sur l'aspect sécurité de divers carburants au regard des appareils électriques présents dans les réservoirs de carburant de véhicules. Les travaux antérieurs avaient servi à évaluer divers aspects de la question, par exemple la sensibilté aux étincelles électriques de certains mélanges au méthanol ou autres, à diverses températures, en présence de circuits électriques alimentant les pompes à carburant, les jauges et autres appareils.

L'un des aspects étudiés qui appelait un exam plus poussé était le recours aux diodes de suppression afin d'accroître la marge de sécurité des pompes à carburant installées en milieu explosif, les travaux antérieurs ayant montré que certains circuits de pompes pouvaient causer l'allumage des vapeurs présentes dans les réservoirs dans certaines circonstances. L'on a déterminé que le succès de l'application de ces doides reposait sur le genre de pompe et le courant utilisé en fonctionnement. En général, le fait que le courant d'alimentation soit assez élevé tend à rendre les diodes de suppression moins utiles comme élément de sécurité dans ces circuits.

Mots-clés: réservoirs de carburant, diodes de suppression, pompes à carburant, sécurité intrinsèque, explosions dans les réservoirs à carburant

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INTRODUCTION

This report is the result of a request from Transport Canada to the Canadian Explosive Atmospheres Laboratory (CEAL) to investigate the effectiveness of suppression diodes in the fuel pump circuits in automobile gas tanks. These diodes suppress reverse transient voltages in inductive circuits, and thereby inhibit sparking which could be ignition-capable. The objectives were to determine the extent to which suppression diodes could be successfully used in fuel pump circuits, and to explain the principles of suppression diode circuits.

The technology falls into the general area of "Intrinsic Safety", a well-known term in the electrical industry. This technology is based on the fact that much electrical equipment can be designed such that any electrical sparking produced under normal operating conditions, or under specified fault conditions, is not capable of igniting a specified explosive fuel-air mixture. In intrinsically safe circuits, sparks that are produced have insufficient energy to ignite explosive fuel-air mixtures, even while using the most easily ignitable gas, and while using an apparatus which is the most effective in producing sparks.

This work was a spinoff from previous work in which the explosive range of a number of fuels as a function of temperature and ignition current were investigated (Ref. 1). The previous work suggested that suppression diodes installed across the terminals of a fuel pump could render the circuit safe whereas previously it was shown to be ignition-capable. In response to this suggestion, Ortech Corp. undertook to further investigate the viability of the suppression diode concept. The Ortech investigation (Ref. 2) concluded that the suppression diodes were ineffective in preventing the ignition of explosive atmospheres.

This report addresses, in more detail than the Ortech work, the concept of fault energy suppression through the use of suppression diodes.

BACKGROUND INFORMATION

If a current is flowing through an inductor, and the current flow is interrupted as might happen in an intermittent electrical fault, the inductor will tend to develop a very high transient reverse voltage in an attempt to maintain the current flowing through it at the original level.

For an ideal inductor, i.e. one which does not magnetically saturate in its operating range, the voltage across the terminals of the inductor as a function of the current flowing through it is expressed by the following ideal characteristic:

$$V = -L\frac{di}{dt}$$

where L = inductance in Henries
V = voltage in Volts
i = current in Amps

If the current instantaneously (or at least very quickly) drops to zero, the value of di/dt, the rate of change of current, goes to an extremely high value. This, multiplied by the value of the inductor (in Henries) yields the value of the transient reverse voltage produced. In this way, transient voltages far in excess of the normal supply voltage can be produced. This technique can be exploited in power supplies, to convert low battery voltages to almost any desired level. With their tendency to momentarily oppose changes in the level of current

flow through them, inductors are more often used in power supplies to smooth out (filter) current fluctuations in DC circuits.

Physically, the mechanism is as follows. Under steady-state current conditions, a magnetic field associated with the current is produced and maintained within the inductor. If the current is interrupted, the magnetic field collapses. The collapsing magnetic field cuts across the coils of wire that comprise the inductor, and induces a reverse voltage in the coil. The speed and strength of the collapsing field determine the magnitude of the induced voltage. Coils wound around metallic cores are able to store considerably more magnetic energy than air-core inductors.

In reality, the above description is further complicated by magnetic saturation (and other) effects when metallic cores are used, as in most practical inductive devices. Magnetic saturation effects will cause an inductor to have nonlinear characteristics which are considerably more involved to model mathematically.

During the period of induced voltage, the inductor is in effect liberating its stored magnetic energy by converting it to electrical energy, and contributing that energy to the electric circuit to which it is connected. Much attention has been paid to the development of magnetic materials which can store the most energy within given space constraints.

Figure 1 shows the reverse transient voltage that is produced in an unsuppressed inductive circuit. Note that the transient voltage is several times that of the power supply voltage.

This explains that where inductive circuits are involved, ignitions of explosive atmospheres under standard test conditions can be obtained at much lower current levels than can be obtained in purely resistive circuits. Inductors store magnetic energy and contribute electrical energy to the electrical fault which is responsible for interruption in current. This contribution is made at the moment the fault occurs. Inductors can easily reduce the safe operating current relative to resistive circuits, by a factor of ten.

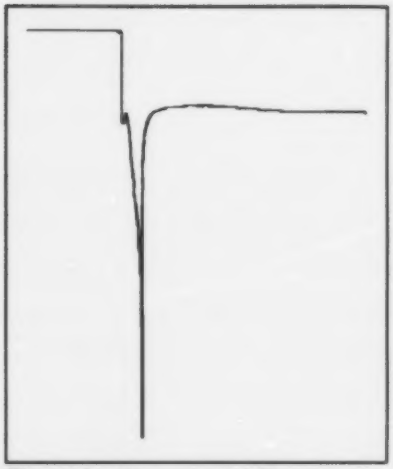

Figure 1 - Unsuppressed Reverse Transient Voltage

Much work has been done in the intrinsic safety industry to determine just how much energy can be involved in a spark discharge before a surrounding explosive fuel-air mixture can be ignited by the discharge. Using the standard IEC breakflash apparatus, the curves shown in Figure 2 were generated several years ago, and have been confirmed many times since then. These curves, which were generated using a series circuit consisting of a 24 Volt DC power supply, air-core inductor, current-limiting resistor, and IEC breakflash apparatus, show the relationship between circuit inductance and the current flowing in the circuit for four

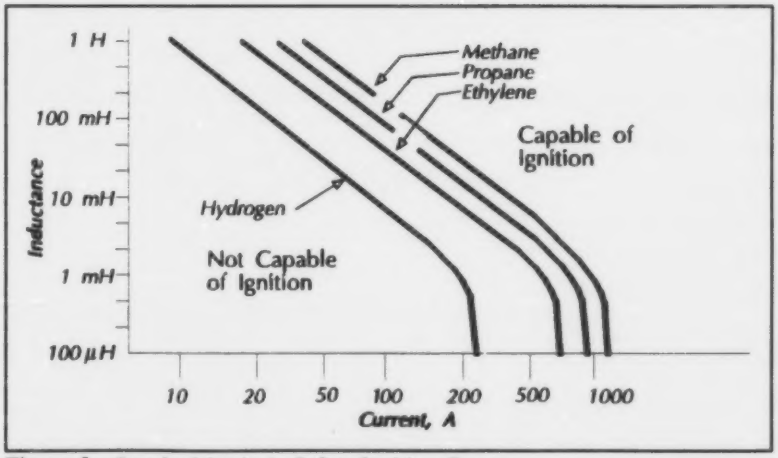

Figure 2 - Standard Intrinsic Safety Ignition Curves; Inductive Circuits, 24 Vdc

different gas-air mixtures[1]. Note that if the circuit inductance is anything over 1 millihenry, the effect of the inductance is to cause ignitions at lower currents. Below 1 millihenry, the inductance has a negligible effect on the circuit.

Since inductors are used so extensively in electrical circuits, usually in the form of relays and motors, circuit designers were faced with the problem of needing to use these devices in intrinsically safe circuits. Intrinsically safe circuits must not be ignition-capable under normal operating conditions, as well as under specified fault conditions, so various approaches were tried to enable inductive devices to be used in these systems.

One attempt involved the use of a single turn of heavy wire around the inductor coil which would absorb the energy from the transient energy produced during the power interruption. However, the most successful approach was through the use of suppression diodes, applied as shown in Figure 3.

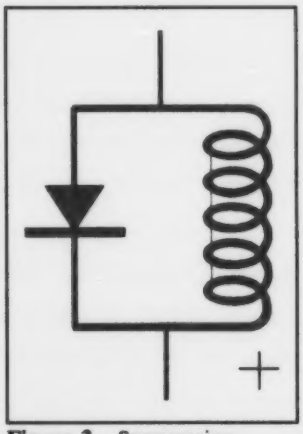

Figure 3 - Suppression Diode and Inductor Circuit

Diodes have the general characteristic that they conduct current easily in one direction, but conduct hardly at all in the opposite direction. As such, they are analogous to a check valve in a hydraulic system. Other diodes, such as Zener diodes, have other additional characteristics, used in specific applications.

Suppression diodes are placed across the terminals of an inductive device, so that when the device is in normal operation,

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[1] The most easily ignitable concentration of gas in air is always used for the generation of these curves.

the diodes do not conduct. Since the transient voltage is produced in the opposite polarity to the normal voltage appearing across the inductor (which is the significance of the minus sign in Eq. 1), the suppression diodes only conduct current when the reverse voltage appears. As soon as the reverse voltage appears, the diode "switches on", and acts as a very low resistance path, which effectively short-circuits the transient overvoltage.

Figure 4 shows the effect of a suppression diode being used in a circuit otherwise identical to the one used to produce Figure 1 (same scale).

Figure 4 - Suppressed Reverse Transient Voltage

Suppression diodes are used extensively in the intrinsic safety industry, and have been for many years, to make safe electrical circuits that would otherwise be ignition-capable.

Most often, a pair of diodes is placed across the terminals of an inductive device such as a relay or DC motor. In such cases, the diodes are often encapsulated in an epoxy or other type of resin to make the coil-diode assembly into one tamper-proof unit. This enables the coil-diode assembly to be considered, for the purpose of intrinsic safety analysis, as one infallible unit. Only one diode is required to suppress the transient overvoltage. The second is a redundancy requirement of intrinsic safety. In fact, in some cases three diodes are required in a parallel arrangement due to redundancy requirements. Some manufacturers have even developed diodes having optimized switching characteristics, such as the TranZorb® (made by General Instrument Corp.), for such applications.

Although the general term "coil" has been used here, the technique is identical when motors are involved.

As mentioned above, the suppression diode short-circuits the transient overvoltage. In spite of this, there is a limit beyond which the technique is no longer effective. The reason for this is that inductance remains in the circuit, and is in fact an integral part of the characteristic of the device. The inductance remains effective so long as current flow is in the forward direction, when the suppression diodes do not conduct and are effectively not in the circuit. At this point, when the amount of inductance in the forward direction is sufficient, the coil is again capable of causing ignitions of an explosive atmosphere.

The topic of suppression diodes has been investigated thoroughly; Reference 3 (Chapter 4) provides a good discussion on the topic and provides other references to the same topic. Reference 3 also provides convincing data on the effectiveness of shunt diodes in electrical circuits, and the limitations of their use.

This report provides information concerning the extent to which suppression diodes can be effective in fuel pump circuits.

METHOD AND OBSERVATIONS

The first step was to calibrate the standard IEC breakflash apparatus, to ensure its capability to ignite at the borderline between safe and unsafe current levels in inductive circuits. This confirmed that the apparatus sensitivity was at the desired level.

The apparatus was found to calibrate normally, first with tungsten electrodes, a cadmium disk, and 8.3% methane-air in a

100 mH standard 24 Vdc 110 mA calibration circuit. The apparatus also calibrated normally when copper electrodes were used to replace the tungsten wires. The borderline between safe and unsafe under these conditions was slightly higher, at 140 mA. This was to be expected, since the copper electrodes are not optimum for causing ignitions at lower current levels. Using 5.25% propane-air and copper electrodes, the circuit calibrated at 110 mA.

All the tests reported below were carried out with the cadmium disk and copper electrodes, using a 5.25% propane-air test gas mixture. The propane-air mixture is somewhat more sensitive to ignition than gasoline-air mixtures, all other things being equal. This study used propane-air mixtures for convenience and because gasoline is a blend of different compounds which varies according to season of the year and supplier.

Two standard automotive fuel pumps were used: Chrysler "Turbo" No. 4203941-19224, and AC No. 1-EP209.

A variety of fast-acting switching diodes were given a preliminary assessment and all were found to have similar suppression performance in this application.

Next, the current characteristics of the Chrysler "Turbo" No. 4203941-19224 fuel pump were observed. The pump drew 9.5 Amps at 13.5 Vdc from a car battery, when the outlet of the pump was blocked, i.e. the outlet of the pump was totally obstructed. Under free running conditions, with no blockage of the pump outlet, the pump drew 3 to 4 Amps from the car battery.

Using a car battery, the characteristics of the pump were as follows. During all testing, the battery was connected to a trickle charger which kept the voltage at a more or less constant

13.5 Vdc. This battery condition approximates electrical system operation in a vehicle:

Table 1

Pump Current vs. Output Pressure for Chrysler "Turbo" No. 4203941-19224 Pump

Pump Current (DC Amps)	Pressure (psig)
4	15
4.5	30
5.4	55
5.7	60
6.6	80
7.3	100
8.4	120 (fully restricted)

The test apparatus was a simple series electrical circuit, consisting of an automotive battery, the IEC breakflash apparatus, and the pump. The automotive battery was connected to a trickle charger at all times to maintain full battery capacity. The fuel pump mechanical circuit was likewise a simple series circuit. The pump inlet drew kerosene from a container to the pump; the outlet of the pump was connected to a restrictor valve with pressure gauge, and thence back to the kerosene container.

The copper electrodes were conditioned by running them in the fuel pump circuit for 5 minutes in the arrangement described above, with a blocked pump outlet.

Note that the electrical load on the pump is a function of the pump back pressure; when the pump is fully restricted with no flow, the pump draws the greatest current from the power supply. Conversely, the pump draws the least amount of current

from the supply when its outlet is unrestricted, resulting in minimum back pressure.

Now that the system was calibrated and conditioned, the actual tests were conducted. The results are summarized in the following table.

Table 2 - Ignition Test Results for Chrysler "Turbo" No. 4203941-19224 Pump

Outlet Pressure (psig)	Diode In Circuit	Diode Not In Circuit
0	No Ignition	no test
15	No Ignition	Ignition
30	No Ignition	Ignition
60	No Ignition	Ignition
80	No Ignition	Ignition
100	Ignition	Ignition
120	Ignition	Ignition

It should be noted that for both fuel pumps tested, the calibration of the IEC apparatus was checked several times during the tests that were carried out to assure accuracy of the results.

The next series of tests, carried out on a smaller AC 1-EP209 submersible pump, were carried out in a manner similar to the above. The load characteristics of this pump were determined to be as follows:

Table 3
Pump Current vs. Output Pressure for AC 1-EP209 Pump

Pump Current (DC Amps)	Pressure (psig)
2.4	10
2.8	20
3.2	30
3.7	40
4.3	50
4.8	60
5	70 (fully restricted)

Table 4 - Ignition Test Results for AC 1-EP209 Pump

Outlet Pressure (psig)	Diode In Circuit	Diode Not In Circuit
0	(no test)	No Ignition
10	(no test)	No ignition
20	(no test)	No ignition
30	(no test)	Ignition
70	No ignition	Ignition
70 (V = 15.5 Vdc)	Ignition	Ignition

DISCUSSION

Chrysler "Turbo" No. 4203941-19224 Pump

Clearly, the results indicate that with the suppression diode not installed, the pump is ignition-capable, even at low output pressures. It should be noted that the manual for this pump specifies normal operating pressure to be 60 psi. However,

General Discussion

with the suppression diode installed, the system was not ignition-capable until the output pressure was in the range 80-100 psi. These results indicate that there was a substantial improvement in the safety characteristics of the system due to the suppression diode. However, the margin of safety with the suppression diode system installed was relatively small.

According to one automotive service manual, the Chrysler "Turbo" No. 4203941-19224 pump should be producing a fuel system pressure of 55 psi, which is very close to the borderline between safe and unsafe operation for this pump.

AC 1-EP209 Pump

The results for this smaller pump paralleled those for the Chrysler "Turbo" No. 4203941-19224 pump, except more safety margin was observed. Without a diode installed, the pump was ignition-capable in the 10-20 psi output pressure range; with the diode installed, ignition could only be obtained by elevating the supply voltage to 15.5 Vdc from the normal test voltage of 13.5 Vdc which was used for all other tests and using the maximum pressure.

Available service information for the AC 1-EP209 pump is not specific as to what the normal fuel delivery pressure should be. It is likely the normal operating pressure would be somewhere around half the maximum possible pressure for the pump, since useful volumes of fuel could be delivered at that rate. With this assumption, the pump could be considered as having a greater margin of safety than the Chrysler unit.

General Discussion

It appears that for the pumps tested, whether or not they are ignition-capable depends on what pressure the pump is delivering when an electrical fault occurs. Lower delivery pressures with consequent lower electrical operating current resulted in non-ignition-capable circuits, but with higher current, the circuit became ignition-capable. This accounts for the apparent discrepancy between the earlier CEAL and Ortech work. The initial CEAL work was done with a pump operating at a low delivery pressure; the Ortech work was done with the same pump operating at a higher delivery pressure.

Based on the measurements reported above, these systems can be analyzed using the rules of intrinsic safety.

In an intrinsically safe circuit, the system first must not be ignition-capable under normal operating conditions. With the diode installed, both pumps would comply with this criterion. Secondly, the system must not be ignition-capable under one fault condition and an elevated power supply voltage (1.5 times the normal maximum power supply voltage). One fault could be a stalled pump, which would draw a much higher than normal current from the electrical system. In an automotive system this elevated fault voltage would be 1.5 times the normal automotive system voltage. Both pumps would probably not comply with this criterion. Thirdly, the system must not be ignition-capable under the conditions of normal voltage and two electrical faults. The Chrysler pump would not comply with this criterion, but the AC pump might.

With this approach, it is unlikely that enough of a margin of safety exists to call the subject fuel delivery systems intrinsically safe. The mechanism for producing sparks, such as broken or intermittent pump connection, is not considered as a fault. Some authorities in the intrinsic safety field believe the mechanism for ignition should be counted as a fault for the

purposes of analysis. Nevertheless, almost all intrinsic safety standards today do not count the mechanism for producing sparks as one of the faults.

Both systems could however be called "non-incendive" in that there are no sparks produced under normal conditions of operation that could ignite fuel-air vapours. Non-incendive systems are also recognized as a method of risk reduction in the electrical industry, and are applied where designers have assessed and accepted the risks involved.

All the tests done in this report were carried out with propane-air mixtures, which are far easier to control precisely than are gasoline-air mixtures or alcohol-air mixtures. There may be a slightly greater margin of safety with gasoline-air or alcohol-air mixtures. It should be noted that for gasoline, the saturated vapour space in the fuel tank is normally not ignitable; for some alcohol fuels, the saturated vapour space atmosphere is ignitable at room temperature.

The fuel delivery systems as designed require a pump size which pushes suppression diode methods to the extremes of their effectiveness. Other methods would probably be less effective. Consideration was given to current limiting devices to limit fault currents, but any increase in complexity in a safety circuit always brings with it additional concerns about reliability. A better approach would be to design the fuel delivery system so that a smaller pump (with suppression diodes) would be adequate for the application. In fact, since the Chrysler "Turbo" No. 4203941-19224 fuel pump is for a larger, relatively more powerful vehicle, it may be that a number of pumps for smaller vehicles that have not been assessed are suitable. The AC 1-EP209 pump is relatively more safe, since it is a smaller pump, and there may well be others.

Finally, consideration could be given to removal of at least the electrical portion of the pump from the fuel tank, which is in fact a basic explosion safety principle: remove the source of ignition from the potentially explosive atmosphere.

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